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Performance Analysis of Two-Way AF Cooperative Relay Networks over Weibull Fading Channels

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Abstract—The performance of two-way amplify-and-forward (AF) cooperative relay networks over independent but not necessarily identically distributed Weibull fading channels is studied. Tight closed form approximations for the overall outage probability (OOP) and the average symbol error probability (ASEP) are derived. The analysis is verified by simulation, and the accuracy is shown to be excellent, especially at high signal noise ratio (SNR). According to the analysis, increasing the fading parameter, the power scaling parameter, or the number of relays, can improve the system performance when the best relay is selected.

Index Terms—Two-way relay network; Weibull fading channel; Outage probability; Symbol error probability; Amplify and forward

I. Introduction

Cooperative relaying techniques have recently gained attention as an efficient way to mitigate fading in wireless networks. Most conventional cooperative relay networks are half-duplex and employ a relaying mode such as amplify-and-forward (AF), decode-and-forward (DF), or incremental relaying [1]. The performance of cooperative diversity networks was investigated in [2]. To enhance performance, selective DF and opportunistic relaying networks have been proposed, and the outage performance and symbol error rate (SER) analyzed in [3]. Further, the average symbol error probability of a multi-branch dual-hop cooperative network in Rayleigh and Nakagami-m fading channels was analyzed in [4], [5]. The strategy of selecting the best relay and *N*th best relay from amongst several relays has been proposed to enhance the spectral efficiency [6]-[9]. The performance of conventional one-way cooperative systems has been investigated extensively.

To further improve the spectral efficiency, two-way AF and DF cooperative relaying protocols have been introduced [10]. In this case, only two time steps are required to transmit a symbol. The outage probability (OP) and symbol error probability (SEP) for two-way AF relaying were analyzed with perfect channel state information (CSI) over Rayleigh fading channels in [11], [12]. In [13], two-way relaying in mixed Rayleigh and Rician fading channels was considered. The exact expressions for OP, SEP and average sum-rate were derived over Nakagami-m fading channels in [14]. However, the above results only consider the performance in terms of single user outage and SER.

Since the quality of service (QoS) requirements for bidirectional links are the same as for two-way relaying, the overall outage probability (OOP) and average SEP performance can be used to evaluate the performance of both links. In [15], the OOP and average symbol error probability (ASEP) performance of two-way AF based relaying protocols over Rayleigh fading channels was investigated. The corresponding performance over Nakagami-m fading channels was considered in [16], [17]. The performance with a cascaded fading distribution such as the cascaded generalized-K distribution [18] has also been investigated. The Weibull distribution has been recommended for mobile radio systems as well as the Nakagami-m distribution [19]. The performance of a conventional cooperative relay network over a Weibull fading channel was analyzed in [20]-[23]. However, the overall performance of two-way relaying has not been investigated over these channels.

In this paper, two-way AF relaying with multiple relays over independent but not necessarily identically distributed Weibull fading channels is examined. Tight closed-form approximations for the OOP and ASEP are derived. These results are validated by simulation, and the effect of the channel parameters on performance is examined.

The remainder of this paper is organized as follows. Section II presents the system model, and the overall outage probability is derived in Section III. The overall error probability is derived in Section IV. Performance results are given in Section V based on the analysis in the previous sections. Finally, some conclusions are given in Section VI.

II. System Model

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The two-way relay model is shown in Fig. 1. Two source nodes S_1 and S_2 exchange information via the best relay R_k. Thus, there is no direct connection between S_1 and S_2. R_k is selected from the set of relay nodes R_j, j=1, 2, ..., N. All nodes operate in half-duplex fashion and are equipped with a single antenna. h_{ij} is the channel coefficient between source node S_i (i=1, 2) and R_j. The channel coefficients h_{ij} are independent but not necessarily identically distributed (i.n.d.) random variables that follow the Weibull distribution.

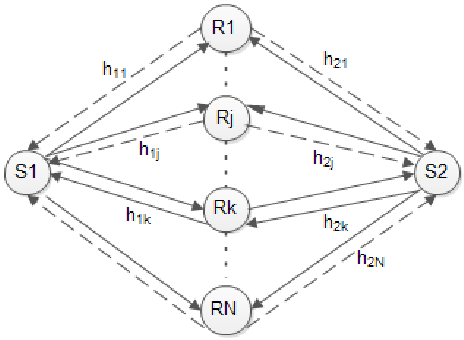

Figure. 1 The two-way AF relay cooperative network.

According to the protocol of two-way relay networks [10], in the first time slot the signal received at the jth relay is given by

$$y_j = \sqrt{P_s} h_{1j} x_1 + \sqrt{P_s} h_{2j} x_2 + n_j \tag{1}$$

where P_s is the transmitted signal energy from S_i, x_i is the normalized signal with unit energy, and n_j is additive white Gaussian noise (AWGN) at relay R_j with zero mean and variance N_0.

In the second time slot, if relay R_j is selected to relay the signal, it scales the received signal by G_j, and broadcasts the resulting signal to S_1 and S_2. Then the signal received at S_i from relay R_j is given by

$$y_{Si} = G_j h_{ij} y_j + n_i \tag{2}$$

With perfect channel state information at R_j, we have

$$G_j = \sqrt{\frac{P_R}{P_s |h_{1j}|^2 + P_s |h_{2j}|^2 + N_0}} \tag{3}$$

where P_R is the transmitted signal energy from R_j. For convenience, let $P_s = P_R$.

After the self-interference is removed, the received signals at S_1 and S_2 are given by

$$y_{S1} = G_j h_{1j} (\sqrt{P_s} h_{2j} x_2 + n_j) + n_1 \tag{4}$$

and

$$y_{S2} = G_j h_{2j} (\sqrt{P_s} h_{1j} x_1 + n_j) + n_2 \tag{5}$$

respectively. The signal-to-noise ratios (SNRs) of the links $S_1 \to R_j \to S_2$ and $S_2 \to R_j \to S_1$ are given by

$$\gamma_{1j2} = \frac{\gamma_{1j}\gamma_{2j}}{\gamma_{1j} + 2\gamma_{2j} + 1} \tag{6}$$

$$\gamma_{2j1} = \frac{\gamma_{1j}\gamma_{2j}}{2\gamma_{1j} + \gamma_{2j} + 1} \tag{7}$$

respectively, where $\gamma_{ij} = P_S |h_{ij}|^2 / N_0$, i=1, 2. When $P_S >> N_0$, (6) and (7) can be expressed as

$$\gamma_{1j2} = \frac{\gamma_{1j}\gamma_{2j}}{\gamma_{1j} + 2\gamma_{2j}} \tag{8}$$

and

$$\gamma_{2j1} = \frac{\gamma_{1j}\gamma_{2j}}{2\gamma_{1j} + \gamma_{2j}} \tag{9}$$

In the second time slot, the best relay R_k is selected to relay the signal, and is selected as follows [15]

$$k = \arg \max_{j\in\{1..N\}} \min\left(\gamma_{1j2}, \gamma_{2j1}\right) \tag{10}$$

The channel coefficient h_{ij} is a Weibull random variable, so the probability density function (PDF) of h_{ij} can be written as [23]

$$f_{|h_{ij}|}(x) = \frac{2\alpha_{ij}}{\bar{\beta}_{ij}^{\alpha_{ij}}} \left(x^{2\alpha_{ij}+1}\right) \exp\left(-\frac{(x)^{2\alpha_{ij}}}{\bar{\beta}_{ij}^{\alpha_{ij}}}\right) \tag{11}$$

where $\bar{\beta}_{ij} = E(h_{ij}^2)/\Gamma\left(1+1/\alpha_{ij}\right)$, $\Gamma(x)$ is the Gamma function, $\bar{\beta}_{ij}$ is the power scaling parameter for the channel between S_i and R_j, and α_{ij} is the fading severity parameter for the channel between S_i and R_j. The PDF of the instantaneous SNR γ_{ij} can be expressed as

$$f_{\gamma_{ij}}(x) = \frac{\alpha_{ij}}{\beta_{ij}^{\alpha_{ij}}} \left(x^{\alpha_{ij}-1}\right) \exp\left(-\frac{x^{\alpha_{ij}}}{\beta_{ij}^{\alpha_{ij}}}\right) \tag{12}$$

where $\beta_{ij} = \bar{\beta}_{ij} P_S / N_0$.

III. Overall Outage Probability

For a two-way AF relaying system employing the best relay R_k, an overall outage event occurs when at least one of γ_{1k2} and γ_{2k1} fall below the threshold γ_{th}. Thus the overall outage probability can be defined as

$$\begin{aligned} P_{out} &= \Pr\left(\min(\gamma_{1k2}, \gamma_{2k1}) < \gamma_{th}\right) \\ &= \Pr\left(\arg \max_{j\in\{1..N\}} \min(\gamma_{1j2}, \gamma_{2j1}) < \gamma_{th}\right) \\ &= \prod_{j=1}^{N} \Pr\left(\min(\gamma_{1j2}, \gamma_{2j1}) < \gamma_{th}\right) \end{aligned} \tag{13}$$

We have

$$\begin{aligned}&\Pr\left(\min(\gamma_{1j2},\gamma_{2j1})<\gamma_{th}\right)\\&=1-\Pr\left(\min(\gamma_{1j2},\gamma_{2j1})>\gamma_{th}\right)\\&=1-\Pr\left\{\frac{\gamma_{1j}\gamma_{2j}}{\gamma_{1j}+2\gamma_{2j}}>\gamma_{th},\frac{\gamma_{1j}\gamma_{2j}}{2\gamma_{1j}+\gamma_{2j}}>\gamma_{th}\right\}\end{aligned} \tag{14}$$

Defining $X_{1j}=1/\gamma_{1j}$ and $X_{2j}=1/\gamma_{2j}$, from (12) the corresponding PDF and CDF are

$$f_{X_{ij}}(x)=\frac{\alpha_{ij}}{\beta_{ij}^{\alpha_{ij}}}\left(\frac{1}{x^{\alpha_{ij}+1}}\right)\exp\left(-\frac{1}{(x\beta_{ij})^{\alpha_{ij}}}\right) \tag{15}$$

and

$$F_{X_{ij}}(x)=\exp\left(-\frac{1}{(x\beta_{ij})^{\alpha_{ij}}}\right) \tag{16}$$

respectively. Then

$$\begin{aligned}&\Pr\left(\min(\gamma_{1j2},\gamma_{2j1})<\gamma_{th}\right)\\&=1-\int_0^C F_{X_{2j}}\left(\frac{1}{2\gamma_{th}}-\frac{x}{2}\right)f_{X_{1j}}(x)\,dx-\\&\int_C^D F_{X_{2j}}\left(\frac{1}{\gamma_{th}}-2x\right)f_{X_{1j}}(x)\,dx\end{aligned} \tag{17}$$

where $C=1/3\gamma_{th}$ and $D=1/2\gamma_{th}$. Substituting (17) into (13) provides the exact overall outage probability. However, this expression cannot easily be evaluated. Therefore an approach similar to that in [15], [18] is used to obtain the following tight closed-form lower bound on (17).

$$\begin{aligned}&\Pr\left(\min(\gamma_{1j2},\gamma_{2j1})<\gamma_{th}\right)\\&\approx 1-F_{X_{1j}}\left(\frac{1}{2\gamma_{th}}\right)F_{X_{2j}}\left(\frac{1}{2\gamma_{th}}\right)\end{aligned} \tag{18}$$

Substituting (18) in (13), the overall outage probability is given by

$$P_{out}=\prod_{j=1}^{N}\left(1-F_{X_{1j}}\left(\frac{1}{2\gamma_{th}}\right)F_{X_{2j}}\left(\frac{1}{2\gamma_{th}}\right)\right) \tag{19}$$

In a similar manner, the CDF of the instantaneous SNR of the best relay R_k can be expressed as

$$F_{\gamma_k}(x)=\prod_{j=1}^{N}\left(1-F_{X_{1j}}\left(\frac{1}{2x}\right)F_{X_{2j}}\left(\frac{1}{2x}\right)\right) \tag{20}$$

IV. Average Symbol Error Probability

The ASEP is another important metric used to evaluate performance. The instantaneous SEP can be expressed as

$$P_e(e\,|\,\gamma)=uQ\left(\sqrt{v\gamma}\right) \tag{21}$$

where $Q(x)=\frac{1}{\sqrt{2\pi}}\int_x^{\infty}\exp\left(-t^2/2\right)dt$, and u and v depend on the modulation employed, e.g. for BPSK $u=1$ and $v=2$ [24]. We then have

$$\begin{aligned}P_e(e)&=\int_0^{\infty}P_e(e\,|\,\gamma)f_{\gamma_k}(\gamma)d\gamma\\&=\int_0^{\infty}\frac{u}{\sqrt{2\pi}}F_{\gamma_k}\left(\frac{t^2}{v}\right)e^{-\frac{t^2}{2}}dt\\&\approx\frac{u}{\sqrt{2\pi}}\int_0^{\infty}\prod_{j=1}^{N}\left(1-\exp\left(-\left(\frac{2t^2}{v\beta_{1j}}\right)^{\alpha_{1j}}-\left(\frac{2t^2}{v\beta_{2j}}\right)^{\alpha_{2j}}\right)\right)\\&\quad\times\exp\left(-\frac{t^2}{2}\right)dt\end{aligned} \tag{22}$$

Asymptotically, $1-\exp(-x)\approx x$ as $x\to 0$, so at high SNRs (β_{ij} large), (21) can be expressed as

$$\begin{aligned}P_e(e)&\approx\frac{u}{\sqrt{2\pi}}\int_0^{\infty}\prod_{j=1}^{N}\left(\left(\frac{2t^2}{v\beta_{1j}}\right)^{\alpha_{1j}}+\left(\frac{2t^2}{v\beta_{2j}}\right)^{\alpha_{2j}}\right)e^{-\frac{t^2}{2}}dt\\&\approx\frac{u}{\sqrt{2\pi}}\sum_{i_1=1}^{2}\sum_{i_2=1}^{2}\mathrm{L}\sum_{i_N=1}^{2}\left(\prod_{j=1}^{N}\left(\frac{2}{\beta_{i_jj}v}\right)^{\alpha_{i_jj}}\right)\\&\quad\times 2^{-\frac{1}{2}+\sum_{j=1}^{N}\alpha_{i_jj}}\,\Gamma\left(\frac{1}{2}+\sum_{j=1}^{N}\alpha_{i_jj}\right)\end{aligned} \tag{23}$$

where α_{i_jj} is the fading severity parameter for the channel between S_{i_j} and R_j, i_j=1, 2, and β_{i_jj} is the power scaling parameter for the channel between S_{i_j} and R_j.

V. Numerical Results

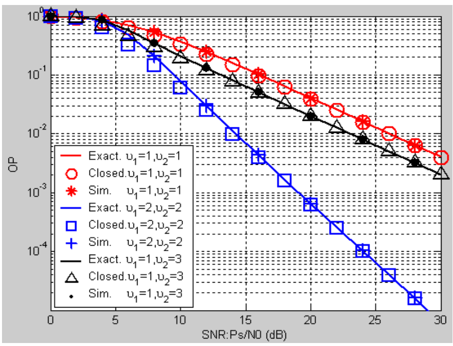

Figure. 2 Overall outage probability for different fading severity parameters.

In this section, we examine the overall outage performance and average symbol error probability for binary phase shift keying (BPSK) modulation. Fig. 2 presents the overall outage probability versus P_S/N_0 with γ_{th} = 1, N_0 = 1, $E(h_{1j}^{\ 2})$ = $E(h_{2j}^{\ 2})$ = 1, fading severity parameters $\alpha_{1j}=v_1$ and $\alpha_{2j}=v_2$, and N=1 relay. This shows that the closed-form expression for the overall outage probability is in good agreement with the exact expression, and this is confirmed by Monte Carlo simulation. In addition, increasing one of v_1 and v_2 provides only a small improvement in the overall outage probability, but at high SNRs, increasing both results in a significant improvement. This is because the overall outage probability is dominated by the smaller of v_1 and v_2, as observed from (14) .

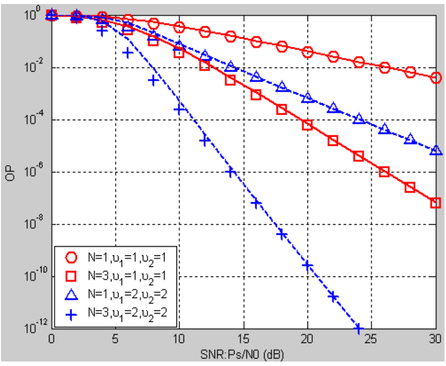

Figure. 3 Overall outage probability for different numbers of relays.

Fig. 3 presents the overall outage probability versus P_S / N_0 for different numbers of relays and fading severity values. The other parameters are the same as for Fig. 2. This shows that increasing the number of relays improves the performance, as expected, particularly for larger fading severity parameters v_1 and v_2. For example, the outage probability is reduced from 10^{-3} to less than 10^{-9} when the number of relays is changed from 1 to 3 with v_1 =2 and v_2 =2 when SNR is 20 dB.

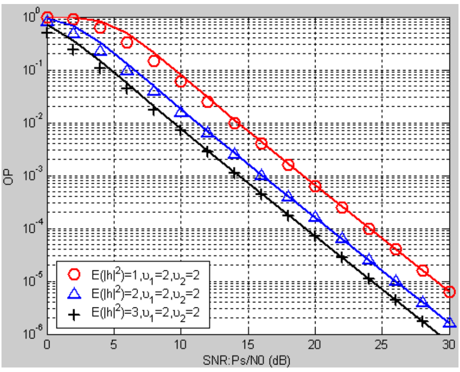

Figure. 4 Overall outage probability for different power scaling parameters.

Fig. 4 shows that increasing $E(h_{ij}^{\ 2})$ improves the overall outage performance. This figure also indicates that for sufficiently high SNRs, the change in performance is a constant as $E(h_{ij}^{\ 2})$ is varied.

Fig. 5 and Fig. 6 present the average symbol error probability for BPSK and quadrature phase shift keying (QPSK) modulation, respectively. From these figures, we find that the ASEP for QPSK is slightly higher than BPSK for the same parameters. However, the performance characteristics are similar for BPSK and QPSK. Fig. 5 shows that in the high SNR region, results using the closed form expression (23) match well with those obtained using (22). Only for large N and small SNR is the difference between (22) and (23) significant. The ASEP is very large in this case, and so has no practical relevance. The ASEP is reduced by increasing v_1 and v_2 or the number of relays N. The ASEP can be reduced significantly by increasing the number of relays N, This also holds for the overall outage probability. As an example, The ASEP is reduced from 10^{-6} to less than 10^{-10} when the number of relays is changed from 1 to 3 with v_1 =2 and v_2 =2 when SNR is 25 dB.

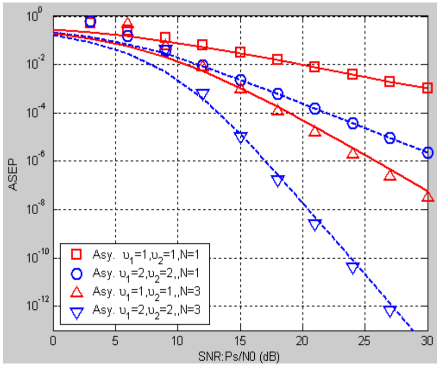

Figure. 5 Average symbol error probability for different power scaling parameters with BPSK modulation.

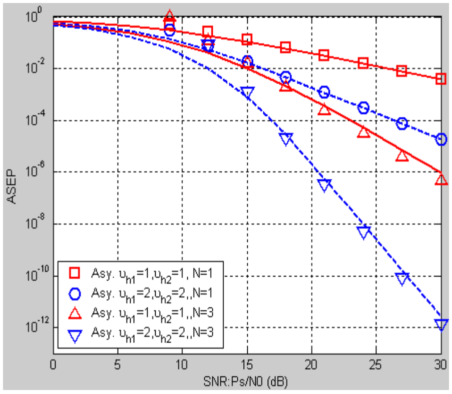

Figure. 6 Average symbol error probability for different power scaling parameters with QPSK modulation.

VI. CONCLUSION

An analysis of two-way AF relay cooperative networks with best relaying over independent but not necessarily identically distributed (i.n.d.) Weibull fading channels was presented. Closed form approximations for the overall outage probability (OOP) and the average symbol error probability (ASEP) were derived. These expressions were shown to be tight, especially at high SNRs. Performance results presented show that the overall outage probability and the average symbol error probability can be improved by increasing the fading severity and power scaling parameters as well as the number of relays.

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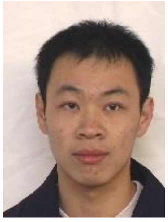

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